ROADMAP TOWARDS FIRST SAS ENGAGEMENT

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Abstract

T-625 helicopter is a light utility multi role helicopter that is designed by Turkish Aerospace Helicopter Group. It is equipped with a four-axis dual-redundant automatic flight control system (AFCS) and this paper presents the stages of the automatic flight control system design of T-625 helicopter. General architecture of AFCS will be provided and the details of SCAS and autopilot systems will be discussed. Safety aspects of dual AFCS will be described together with an overview of safety-critical system development. Stages of AFCS control law design and their implementation to the Flight Control Computers will be briefed. Details of conducted system tests at the hardware in the loop engineering simulator, as well as during ground and flight tests will be discussed. In overall, this paper summarizes the studies performed towards first autopilot engagement of T-625 helicopter and introduces results from both ground and flight tests.

1. INTRODUCTION

The T-625 Gökbey Helicopter Program was initiated in 2013 and it is being designed and developed by Turkish Aerospace. T-625 is a dual-engine 6 tons class multi-role helicopter, which can easily be adapted to perform diverse types of different mission profiles for civilian and military operators. It is designed for passenger transport operations and parapublic/governmental needs such as VIP, Air Ambulance, Search & Rescue, Cargo, and Off-Shore. First prototype of T-625 helicopter has performed its maiden flight in September 2018 and starting from June 2019, certification and qualification flight tests are being performed [1].

Design of T625 maximizes situational awareness and minimizes pilot workload through a modern glass cockpit and an advanced automatic flight control system (AFCS). The glass cockpit, which is developed by ASELSAN, consists of two-touch screen Integrated Modular Displays (IMD's) and two Touchscreen Cockpit Control Units (TCCU's). IMD's provide the interface between the helicopter system and pilots, whereas TCCU's are used for data entry and soft controls.

Interfaces between basic helicopter systems and IMDs/ TCCUs are provided by two Data Concentrator Units (DCUs).

The Automatic Flight Control System (AFCS) enhances the stability and handling qualities of the helicopter and provides autopilot functions. T625 is equipped with a four-axis dual-redundant Automatic Flight Control System which provides stability augmentation functions, basic modes, flight director (FD) modes, self-test, and monitoring functions. A general overview of AFCS and its interfaces with other aircraft systems are shown in Figure 1.

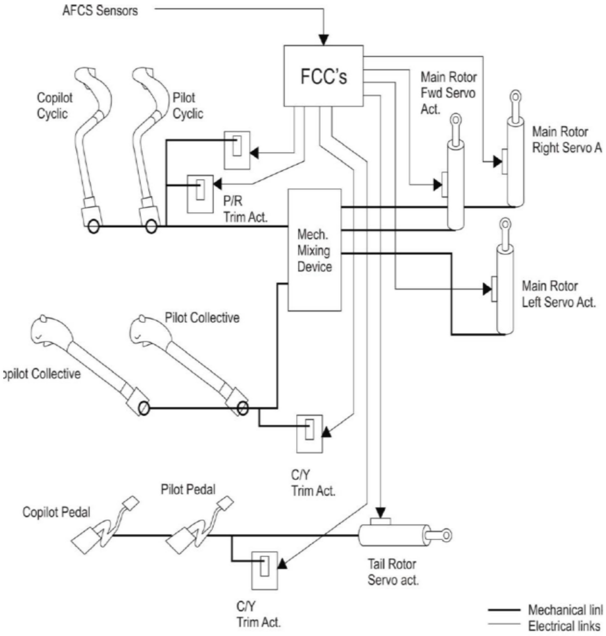

Figure 1: General AFCS Architecture

AFCS architecture is composed of two independent flight control computers (FCCs), four trim (parallel) actuators, eight stability and control augmentation system (SCAS) actuators and an AFCS control panel. FCCs are developed according to RTCA/DO-254 design assurance guidelines [2] and function as central processing and interface elements of the AFCS. T-625 is equipped with four full-authority trim actuators as shown in Figure 1, for each control axis. These actuators are installed parallel to pilot's controls and receive independent command inputs from two FCCs. They provide artificial force feel to the pilots through an electro-mechanical clutch unit, which can be suspended by force trim release buttons on controls or permanent trim release buttons on the AFCS control panel. Main and tail rotor actuators are equipped with limited-authority dual series actuators that are utilized for performing high bandwidth closed loop control. These electro-hydraulic actuators provide short term stabilization to the helicopter in response to the commands received from both FCCs. Last component of the AFCS system is the AFCS control panel, which provides an interface to the pilots for controlling the autopilot system. By the help of AFCS control panel, channel selection, AFCS mode selection and test function can be performed.

Other than flight controls, main and tail rotor actuators, AFCS has interfaces with other avionics equipment including IMDs, DCUs, Air Data Computers (ADC), Attitude and Heading Reference Systems (AHRS), Radar Altimeter and Weight-on-Wheel switches. For each of these equipment, the AFCS has a sensor selection and consolidation capability.

The AFCS provides a fail-safe design that is fail passive in most cases. Basic functionality of the system is dual-channel stability augmentation (SAS mode) that can operate for both hands-on/off flight. Readings from AHRSs and ADCs are processed within FCCs for generating necessary electrical commands to the actuators. FCCs also provide sensor interfaces for reading the position and direction of the SCAS and Parallel Trim actuators. Position sensing is achieved by monitoring the Linear Variable Differential Transformers (LVDTs) for SCAS actuators and resolvers for trim actuators. These readings provide feedbacks for close-loop position control and are being utilized for monitoring end/around signals, e.g., mistrim or failure scenarios like actuator hard-over, jam etc.

Functions provided by the automatic flight control system are given in Table 1.

Table 1: AFCS Functions

Basic Modes	Stability and Augmentation System (SAS)
	Attitude Hold
	Auto-trim
	Turn Coordination
	Couple/Decouple Mode
Flight Director Modes	Upper Functions
	Navigation Functions
	SAR Functions
Failure Monitoring	Fault Detection and Annunciations
Test Functions	Pre-Flight Test Function
	Test Support Function*

*Used only for AFCS Development Tests

Basic mode functions provide helicopter stabilization and includes ability to hold helicopter attitudes along pitch, roll and yaw axes. Flight director modes provide control of helicopter attitude, speed and heading for conducting upper control functions like barometric altitude hold, indicated airspeed hold, hover hold, go around etc. In addition to these upper functions, flight director modes also include navigation functions (VOR, ILS, FMS) like approach and back course as well as Search and Rescue (SAR) modes like Mission on Target. Preflight test functions are used to check key pilot interfaces together with the behavior of parallel (trim) and series (linear) actuators on ground.

Since AFCS of T-625 helicopter is under development, a test support function is added to the flying prototypes, which includes an external test unit denoted as Development Test System (DTS). Development test system consists of an onboard laptop PC (i.e., DTS PC), a control panel and a touch-panel. DTS-PC has interface with FCCs for monitoring AFCS status information and AFCS variables. This interface also allows flight test crew to modify control law gains during flight and inject different actuator commands through SCAS and trim actuators.

In the following sections of this paper, design stages of T-625 AFCS will be discussed in detail. First part will focus on system development overview, requirements definition and their implementation to the AFCS software, as well as requirements validation & verification. Then, information about AFCS control law development activities will be provided. This section will be followed by system tests, which are performed at engineering simulator and during helicopters' ground and flight tests.

2. OVERVIEW OF SYSTEM DEVELOPMENT

Since December 2010 when revision A of the document ARP-4754 [3] was released, it is being used as a guideline for development of civil aircraft and systems. Together with other Aerospace Recommended Practice (ARP) and DO (ED for Europe) documents, it covers a well-defined aviation ecosystem. Regarding the ARP4754-A, there are numerous in-depth publications, and this paper does not fit in to comment on or analyze the ARP4754-A process. Rather, this paper briefly discusses how to manage this process and what is read between the lines.

Without going into the details of ARP4754-A process, it is still important to mention its general phases. ARP4754-A divides system development process into planning and aircraft requirements identification (i.e., aircraft function development), allocation of aircraft functions to systems, development of system architecture and allocation of system requirements to items, design of items (including software and hardware), integration of items for system verification and finally system implementation including the developed software and hardware.

ARP4754-A is the centerpiece of systems development but must consider ARP4761A [4] safety standards while defining safety requirements and system architecture. Adding hardware DO-254 [2] and software DO-178C [5] guidelines to these standards lead to the big-avionics-picture (Figure 2). The big-avionics-picture guides avionics system developers through the process by specifying which design documents and test documents are required and/or needed to be created. Adopting the steps of these processes will assure a certified and safe aircraft.

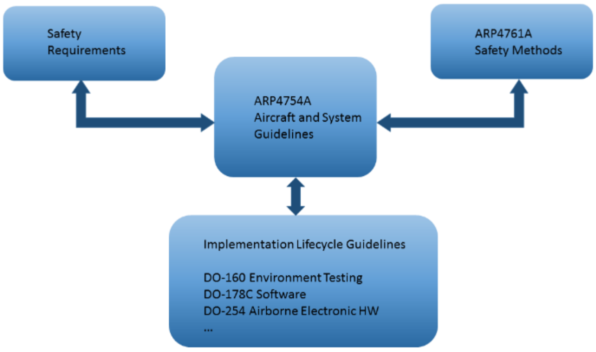

Figure 2: Big-avionics-picture

3. CHARACTERISTICS OF GOOD REQUIREMENTS

In the whole and in retrospect of the whole development process, one of the most important building blocks is to define good requirements, which requires high discipline and persistence as requirements are the starting point of any design. Creating requirements is an art in engineering that involves many challenges. Art (in the artificial sense) is associated with talent but writing satisfactory requirements could be learned. This, in return, can be reflected throughout the organization, and will lead to greater visibility, greater safety, less rework, and improved productivity. Requirements are used to define the behavior, attributes, and properties of a future system. They not only form a basis for design and design optimization, but also show backward and forward traceability to sources and the history of changes. In other words, they enable a logical approach to change management.

In principle, it is useful to set the usage of correct terms first, then to generate an editorial checklist for product requirements, a general goodness checklist and an additional checklist for validation. It is important to address some general requirement characteristics which should be a part of these checklists. Requirements should state ‘what’ is needed, not ‘how’ it is to be provided, and they should be written with certain properties. Having an atomic structure, being concise, consistent, and complete are some of these properties. Written requirements should also be unambiguous, traceable, verifiable, and viable. Those listed properties can be embedded in the requirements tool being used. For e.g., if commercially available IBM DOORS [6] is being used as the requirement management tool, dxl (DOORS extension language) scripts can be written for ensuring the properties defined above. These scripts will enable each user to run and pass the previously defined rules before applying changes to the baseline. Running dxl scripts on the requirements is convenient since they are text based.

4. SAFETY-CRITICAL DEVELOPMENT

Systems engineering is a broad field where only general guidelines can be given. In this section, difficulties and demands that were faced during development and deployment process of an Automatic Flight Control System to a manned helicopter is discussed with some examples.

Looking at the conventional architecture of an autopilot system, it can be divided into three main categories. The first category is the flight control computer (FCC), second one is the actuators, and third category is the pilot interface equipment. Each of these main categories can be broken down into further areas. To solidly design each of these system areas and to meet the standards mentioned above, it is fundamental to form appropriate groups for sharing domain expertise. Experience has depicted that having a team composed of Flight Mechanics, Autopilot System Design, Flight Control Law Design, Integration, Software Design and Software Verification disciplines is useful, productive, and effective for this mission. These disciplines, in turn, can be formed from aerospace, mechanical, electronics, mechatronics and computer science engineers where all disciplines together form an indispensable teamwork.

Quantity and quality are always a topical issue. Keeping and sustaining the balance of both is a never-ending challenge. In the aircraft industry and particularly in the development of so-called safety critical systems, the question of quantity and quality is easier to answer. Quality, in other words "safety first" should always be the top priority. Experience has shown that there are key factors that must be carefully considered and are constantly addressed in the development stage of safety-critical systems.

One of these key factors is well-qualified personnel. Safety-critical systems are implemented through people and development of such systems requires years of expertise. Well-documented system architecture, a detailed sub-architecture and requirements definition are some other key factors. System architecture and requirements should focus on safety and these requirements should be validated for correctness and completeness. It is essential that safety is an integral part of all levels of development. Finally, it is critical to have testing at all levels for refining the development process.

5. AFCS CONTROL LAW DESIGN

Initial step of designing a controller for a new prototype is to analyze inherent stability characteristics of the rotorcraft. Presence of a high-fidelity helicopter model can be a real advantage at this stage since it allows design engineers to foresee flight characteristics beforehand.

TOROS, built in MATLAB-Simulink® environment, is an in-house tool developed by TA, which is used to construct high fidelity non-linear mathematical model of a helicopter. It is utilized to support flight mechanics design and analysis, to perform handling quality analysis, and to design control laws for the automatic flight control system. Models generated using TOROS can be deployed into a real-time flight simulator as shown in Figure 3, for performing pilot in the loop simulations The principal structure of TOROS can be found in Refs. [7], [8]. Each rotorcraft component is modeled individually in a modular structure. Contributions of each component to the equations of motion are calculated based on detailed rotorcraft characteristics. As described in Ref. [9], light utility helicopter model constructed in TOROS is also validated with commercially available FLIGHTLAB® software in terms of trim, linearized system, and nonlinear response results.

First step of the control law design is to obtain high-order linear model of the helicopter around previously determined flight conditions. It is known that these linear models represent nonlinear model behavior around the specified trim points. When flight-dynamics simulation model for piloted evaluation is considered, typical frequency range of applicability is about 0.3 – 12 rad/s [10] which is the rigid body motion. High order models contain many states dependent to each other and states that are decoupled from 6-DoF helicopter model. Considering the frequency range of interest for the controller design, higher-order linear helicopter models can be reduced into lower order models. Residualization of high frequency dynamics onto the rigid body motion preserves the steady effect of fast dynamics. Reduced order linear models exhibit a similar behavior to the high order linear models within the desired frequency range.

After obtaining low order helicopter model, eigenvalue analyses are performed, and aircraft modes are decoupled into longitudinal and lateral dynamics by disregarding control couplings. These simplified models resulted in more convenient application of classical control techniques to the given problem. After defining performance metrics and design objectives for obtaining a robust controller, desired control laws are applied to the corresponding axes first for stabilization and basic mode controls and then for upper mode control functions.

6. ENGINEERING SIMULATOR

During preliminary stages of the T-625 helicopter program, the simulator environment was first constructed as a system integration laboratory (SIL), for performing hardware in the loop tests, especially for development and testing of the automatic flight control system (AFCS). However, with increased flight dynamics model-fidelity, and integration of real avionics, SIL transformed into a pilot in the loop preparation facility, which is being utilized like a training simulator for the flight test crew.

Figure 3: T-625 Engineering Simulator

T-625 has a fixed based simulator as shown in Figure 3 for pilot in the loop and hardware in the loop simulations. The simulator is equipped with the same glass cockpit as the prototypes, which consists of two touch screen IMDs and two TCCU's. The outside view from the cockpit is illuminated by twelve projectors that reflect their images to a projection dome. The resulting field of view is 80 degrees in vertical and 210 degrees in lateral plane which is enough to support any given helicopter maneuver. This wide field of view also enables pilots to visualize the ground and orientation of the helicopter through the chin windows.

The engineering simulator is equipped with conventional type flight control system including cyclic, collective and pedals. Flight controls are connected to the trim actuators by mechanical linkages just as in the real prototypes.

Other than glass cockpit and flight controls, the simulator is also equipped with other avionics. These avionics equipment include real flight control computers (FCCs), AFCS Control panel, DTS control and touch panels and other mission critical panels like engine control panel (ECP), fuel system control panel and landing gear control panel. All AFCS related avionics hardware and software, which is being used in the engineering simulator, are identical with the ones in the prototypes.

During development flight test stages of T-625 helicopter program, simulator tests proved themselves to be invaluable tools not only for preparing the flight crew for the upcoming flight tests, but also for providing a means to the engineering team in the telemetry station what to expect during the real flight test. Additionally, simulator flight data reduction reveals any shortcomings in the flight test technique or the data reduction method itself, allowing the flight test team to modify and improve the test technique or data reduction method before the real test flights took place. In this regard, simulator tests increase flight test safety and ensure overall cost reduction. With all these advantages presenting themselves early in the program, simulator test flights quickly became a prerequisite for any real test flight [11].

Since hardware and software of the FCCs that are being used in T-625 helicopters are both innovative designs, a testing facility was required for performing both software in the loop and hardware in the loop simulations. At the current stage, the system integration laboratory which also includes the engineering simulator, has this capability. New revisions of AFCS software and any desired design modifications can easily be assessed in this facility.

Other than performing tests at systems level, pilot-in-the loop simulations also played a vital role during first engagement of the stability augmentation system. Like open loop envelope expansion cases, simulator flight tests were conducted in the engineering simulator to increase familiarization of flight test crew to the AFCS. In addition, different controller gain sets were tried, and various stimuli injections were given using DTS, prior to first flight with the autopilot. For increasing system safety, a simulator test campaign was also conducted for critical AFCS failure scenarios, especially for testing actuator hard-over failures.

7. GROUND TESTS

Performing ground tests on the prototypes was another critical stage prior to performing AFCS testing during flight. These tests include procedures that were performed on ground for verifying correct installation and operation of the AFCS, as well as supplementary tests like ground resonance and structural coupling.

7.1. Ground Test Procedure

A competent ground test procedure should cover majority of the critical functions that can be assessed on ground. Experience showed that, helicopter level ground testing steps should include equipment verification, testing input and output controls, checking warning information, testing trim and series actuators, examining gain polarity, testing AFCS basic modes and finally performing a preflight test.

In AFCS equipment verification step, installations as well as circuit breaker status and configurations of both related software and hardware should be reviewed. This test can be followed by checking connections and interfaces of AFCS with related flight controls and other avionics equipment. In general, status of connections, input/output data links and inputs provided from flight controls are tracked through a diagnostic page. For checking warning information, redundancy tests could be performed for verification of crew alert system (CAS) display messages and aural alerts related to AFCS.

Trim actuator ground test steps include both resolver sensor readings for ensuring that pilot controls stay within rigging tolerances, and testing force feel system against any undesirable discontinuities. In terms of series actuators, engagement tests could be performed by energizing the solenoid valve and controlling flow to the SCAS actuators by the electrohydraulic servo-valve. Before testing AFCS basic modes, it is essential to verify gain polarity, which is a control step for series actuator command directions. In this step, SCAS actuator commands are generated, and desired directions are verified with respect to controlled AHRS (or other inertial sensor) movements. These ground tests could be followed by AFCS basic modes test which is utilized for verifying basic modes functionality and axis actuation capabilities. These tests include evaluation of control authority and performance of the actuators as well as visual checks on primary flight display indications (mode selection, changing reference bugs etc.).

After completing aforementioned procedures, AFCS preflight test, in which both FCCs send commands to all series and parallel actuators to verify actuator feedbacks, should be performed on ground. This test is an automated test that can be initiated through ACP and is the last step of AFCS ground test procedures before performing a flight test with engaged autopilot.

7.2. Ground Resonance Tests

As mentioned in general AFCS architecture, T-625 prototypes are equipped with an external test unit, DTS, for monitoring, debugging, and setting parameters within AFCS. This test unit can also be utilized for making stimuli injections which enables usage of DTS for other testing purposes.

Ground resonance tests are one of these examples, in which ground runs were performed to demonstrate ground resonance stability margin. During these tests, excitations were given to main and tail rotor blades through SCAS actuators for observing helicopter response. Control axis, stimulus types (additive / replacive), injection functions (sine, chirp, pulse etc.) and related amplitude / frequency information are set and armed through DTS touch panel by the flight crew. After these parameters are set, stimuli injections are given through DTS control panel (Figure 4).

Figure 4: DTS Control Panel

Figure 5 represents a stick stir input produced by DTS that is used to excite the regressing in-plane mode of the main rotor. Input commands of linear actuators in longitudinal axis are plotted against longitudinal cyclic measurements in multi-blade coordinate and damper stroke of reference main rotor blade. Notice that chirp excitation provided by the SCAS actuators enabled rotor design group to determine highest response frequency.

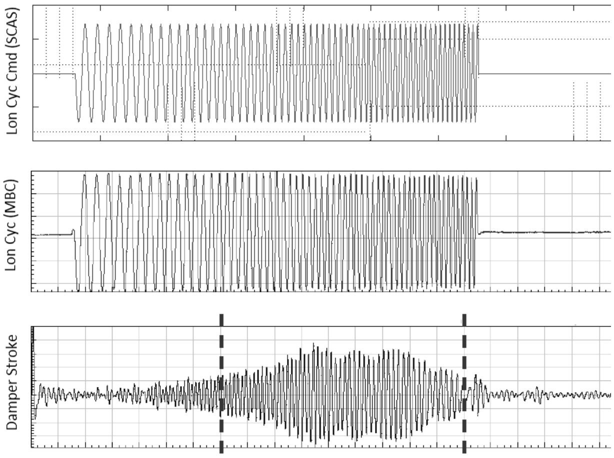

Figure 5: Sample Results from Ground Resonance Test (Injection is given from SCAS Actuators)

7.3. Structural Coupling Tests

Other than performing AFCS preflight test and ground resonance tests on ground, structural coupling tests were performed for measuring structural responses that are picked up by the aircraft inertial sensors. Objective of these tests was to identify the characteristics of relevant structural modes and to test the implemented notch filters to the AFCS algorithms.

These tests were executed by injecting sinusoidal inputs generated from DTS computer to the control surface actuators of the helicopter at different collective pitch positions. It was critical to determine the ideal excitation amplitude in each control axes so that sinusoidal oscillations were sufficiently high, while actuator non-linear effects (actuator position / rate limits and monitoring system constraints) were avoided. In these tests, response of helicopters principal modes to the excitations with differing amplitudes and frequencies were identified.

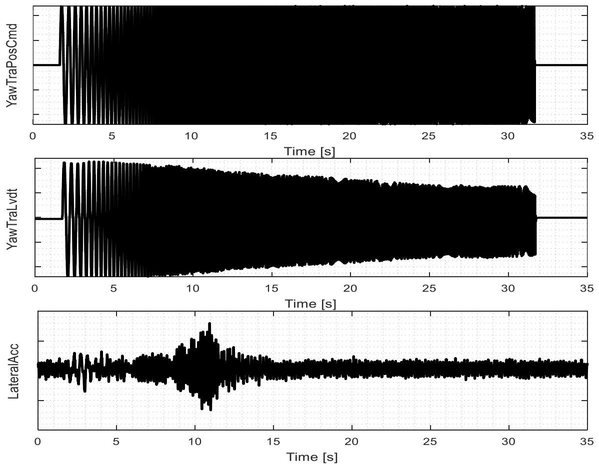

Figure 6: Structural Coupling Test (Pedal Sweep @ 100% NR, 20% Collective)

Figure 6 represents a result from pedal sweep test, which was performed with 100%NR at 20% collective input setting. Chirp input commands are provided by the AFCS to tail rotor SCAS actuators. Notice that first plot represents position commands, whereas second and third plots represent position readings of tail rotor series actuator via LVDT and lateral acceleration reading from AHRS, respectively.

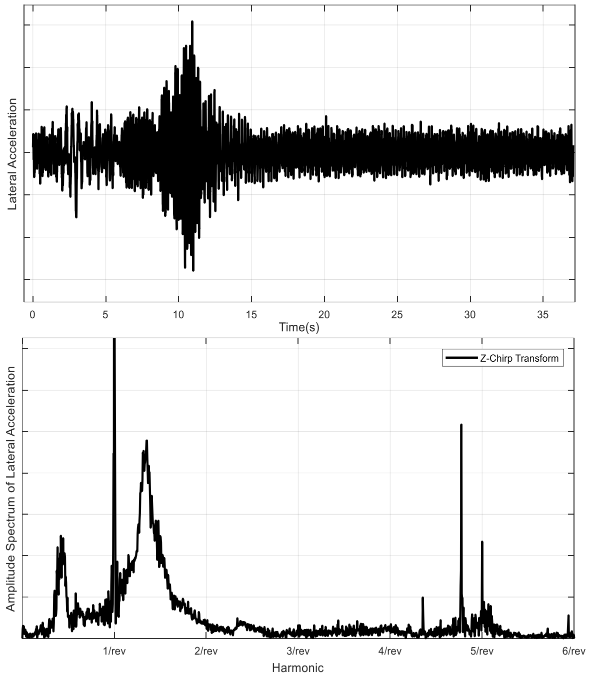

Figure 7: Lateral Acceleration Output Frequency Content

Frequency content of the lateral acceleration output is provided in Figure 7. Notice that, other than rotor induced oscillations at 1/rev frequency, pedal inputs resulted in oscillations around 0.45/rev and 1.35/rev frequencies. Investigation of sources of these modes showed that oscillations around 0.45/rev are resulted from ground contact of tires and this content becomes indistinguishable during light on wheel and flight tests. Examining the results showed that, the content around 1.35/rev is related with a structural mode of tail cone, which is also observed during flight tests. As a result, a notch filter is added to the design for providing attenuation around this frequency.

8. FLIGHT TESTS

After completing prerequisite tests on ground and in engineering simulator by training the flight crew, next step was to test the AFCS in flight. For a helicopter project that is under development, first engagement of the stability augmentation system (SAS) is critical for safety of flight. As flight dynamics model has not been verified for the whole operational envelope, controller parameters (control gains and limit parameters) are increased with a build-up approach, to compensate uncertainties between the helicopter model and the actual helicopter.

Initial step was to set control limits and commands to zero (like open-loop flight case) for observing whether the monitoring functions and AFCS algorithm is running as expected during flight or not. At this step commands were not applied to the actuators. In the upcoming steps, control gains and limit parameters (i.e., controller parameters) are increased with the aid of the DTS. Similar to stimuli injection cases, new parameter set was injected by the flight crew to the running FCC while AFCS modes were inactive. Then by engaging the autopilot and selecting the specific mode (SAS for this case) from ACP, control function was made active. Although attentive flight was performed, to disengage AFCS in case of an inadvertent or erroneous operation, short term behavior of the helicopter was also monitored by the design engineers through the telemetry station to avoid critical flight conditions. After familiarization step, pulse inputs were injected at each axis to quantify the increase of rate damping with the increased controller parameter. Tests were then repeated at different flight conditions (hover, low speed & high – speed) for evaluating the initial controller parameters.

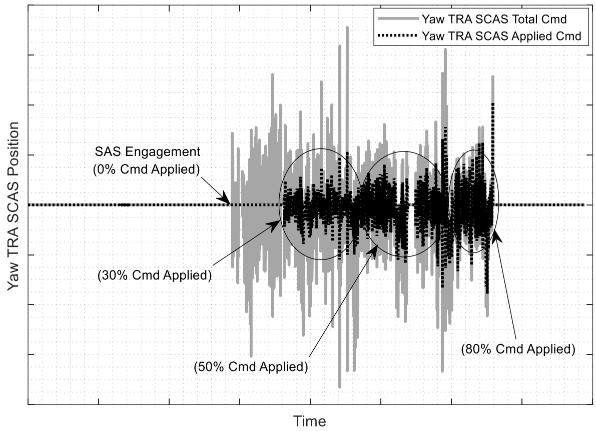

Figure 8: Tail-Rotor Commands Produced vs. Applied

The output of command scaling is provided in Figure 8. During this flight test, using parameter update feature from DTS, commands were applied at different control authorities. In the given figure, computed commands through AFCS are plotted against the applied commands. Notice that control authority is increased (i.e., applied commands) as the flight test progresses. By altering controller parameters from DTS, applied commands through tail rotor SCAS actuators were increased from 0% to 80% using build-up approach.

Other than command scaling, pulse inputs are injected at each axis during flight tests. Figure 9 represents rate changes for unit control input during hover for different gain sets. Reduction in rates justifies the increased damping effect of SAS. Similar results can be observed in Figure 10 which compares pitch rate response of the helicopter to the same pulse input with different gain sets.

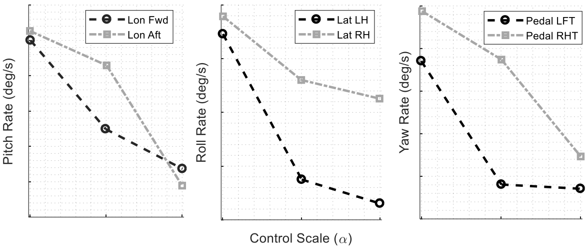

Figure 9: Rate Changes with Control Scale

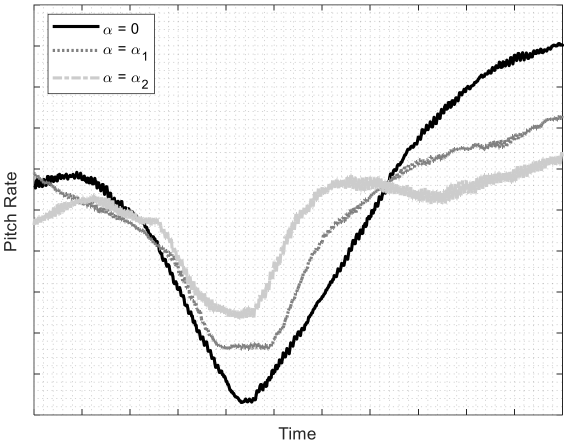

Figure 10: Helicopter Pitch Response Comparison with Different Control Scaling to DTS Pulse Inputs

Flight test results are also compared against engineering simulator test results, which were performed by the flight test crew before the actual flight. For this comparison, a control sensitivity parameter, which depends on 'maximum angular rate obtained per unit input' is defined against control scale. Figure 11 represents a sample output of the control sensitivity comparison between flight test and simulator test data in longitudinal axis. Notice that unit rate changes for open-loop test cases as well as their variation with control scaling is similar for both cases. This means that, for the tested configuration and condition, simulator response resembles the response gathered from flight test quite well.

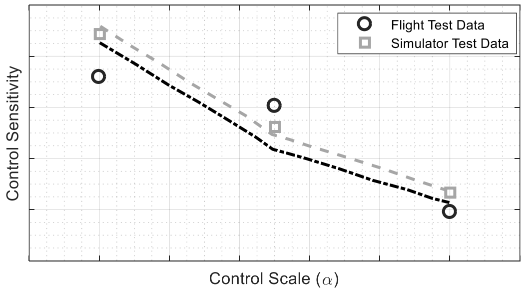

Figure 11: Control Sensitivity Comparison with Different Control Scaling (Pitch - Axis)

In current stage of the T-625 helicopter program, development tests are ongoing for the AFCS system. Up to now, SAS, and Attitude Hold (ATT) modes were successfully tested at different flight conditions and fine tuning of controller parameters (and gain scheduling) are ongoing. After completing these steps, development flight tests of upper modes will be executed.

9. CONCLUSION

This paper summarizes the studies and experience gained from successful engagement of T-625 autopilot system. An overview of safety-critical system development is provided together with stages of AFCS design and implementation. Importance of hardware and software in the loop simulation environment for avionics equipment development was explained. Benefits of adding a development test system to the helicopters as well as the build-up methods that were applied for AFCS testing on ground and in-flight are briefly discussed.

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